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Spectroscopy of multiply charged titanium ions in high-density magnetic fusion plasmas

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Abstract. The M-shell line emission from multiply charged titanium ions has been investigated at the sustained spheromak physics experiment in Livermore. Titanium was introduced into the relatively low-temperature, high-density magnetically confined spheromak plasmas using a titanium gettering system. The measurements were done using a high-resolution grazing-incidence spectrometer with a 1200 lines/mm grating and a Photometrics charged-coupled device camera. Spectral lines from the transition array $3s^2 3p^k$ - $3s^2 3p^{k-1} 3d$ in argon-like Ti^{4+}, chlorine-like Ti^{5+}, and sulfur-like Ti^{6+} have been observed in the 240 - 370 Å interval.

1. Introduction

Titanium is a transition element of interest in magnetic confinement fusion (MCF) research. Since 1974 titanium has been used in fusion experiments to reduce impurity concentrations and control hydrogen recycling [1]. As radiation losses have large effects on the energy balance in fusion plasmas, it is of utter importance to reduce ion impurities to be able to heat plasmas to thermonuclear temperatures. Titanium is deposited on plasma-facing surfaces by means of the so-called titanium gettering method. In this process titanium is evaporated inside the MCF vacuum vessel and deposited on the interior surfaces. This way the titanium will not only reduce the impurity concentrations by binding to various gas molecules present in the device, but also by burying impurities on the walls [1].

Ti has been spectroscopically investigated in many MCF experiments. Especially x-ray spectra of the K-shell emission from highly charged titanium ions have been observed in several tokamaks [2, 3, 4, 5, 6, 7], but also EUV measurements have been performed, see e.g. Ref. [8] for observations of strong Ti lines on the PLT tokamak. More recently Ti lines have unexpectedly appeared in EUV spectra from the NSTX spherical torus, i.e. from plasmas where no Ti gettering is used [9]. The study of titanium spectra in fusion plasmas is also of general interest to better understand the spectra of multiply charged ions from mid-Z elements in both laboratory and astrophysical environments. When the 3p subshell gets partially stripped, starting with chlorine-like ions, the spectra get relatively complex due to the numerous coupling combinations of angular momenta.

Here we have investigated the titanium 3p - 3d M-shell EUV emission at the sustained spheromak physics experiment (SSPX) [10, 11]. The SSPX spheromak research facility, in operation from 1999 to 2007 at the Lawrence Livermore National Laboratory in California, was a project among innovative confinement concepts in magnetic fusion research, aimed at

investigating the feasibility of spheromaks as potential fusion reactors [12]. Typical electron densities of SSPX plasmas were a few times 10^{14} cm^{-3}, and were thereby denser than most tokamak core plasmas. This made SSPX a good test bed for the study of spectra not readily attainable in other devices.

2. Measurements

The SSPX spheromak produced toroidal hydrogen plasmas confined in a copper flux conserver coated with tungsten to minimize sputtering of wall material. On the plasma-facing components a 10 nm layer of titanium was deposited by titanium gettering [12]. The titanium deposition effectively helped to reduce the amount of impurity ions, but, as a side effect, also introduced titanium ions into the spheromak plasmas. For our measurements we utilized this as a convenient injection method.

The instrument used for the titanium spectroscopy was a flat-field grating instrument as described in Ref. [13]. Employing a 1200 lines/mm grating, the high-resolution EUV spectrometer achieved a line width of around 0.3 Å full width at half maximum. The spectrometer had a tangential line of sight of the spheromak magnetic axis through the midplane of the toroidal plasmas. The spectra were time-integrated and recorded with a Photometrics charged-coupled device camera.

The spectra were wavelength calibrated using first and second order lines from oxygen ions present in SSPX [14, 15] and lines from the Lyman series in helium, which was puffed into the device to provide reference lines. By analyzing many SSPX shots we could recognize which lines belonged to Ti and which originated from other plasma impurities such as C, N, O, and W.

3. Results

By studying subsequent discharges after titanium gettering it was clear the strong line emission observed in the 240 - 280 Å interval originated from M-shell titanium ions. The lines were very strong in the first shots after the titanium deposition and got weaker as the Ti wore off the walls during discharges and got pumped out from the vacuum vessel. We have identified strong lines from four times ionized argon-like through six times ionized sulfur-like titanium. The strongest lines are of the $3s^2 3p^k$ - $3s^2 3p^{k-1} 3d$ transition array, which is listed in Table 1. We have used line lists from Kelly [16] and the NIST Atomic Spectra Database [17] to identify the observed features. The listed data are taken from measurements by Svensson and Ekberg 1968 [18] and Svensson 1976 [19].

Shown in Figure 1 is a spectrum from SSPX shot # 18633 displaying the strong titanium lines in the 240 - 300 Å interval. In this discharge the charge balance seems to be dominated by the chlorine- and sulfur-like ions, indicating an electron temperature of around 50 - 70 eV. In the spectrum there are additional lines (some that are blended with those from titanium), mainly from oxygen. The Ti^{6+} line at 254.0 Å has previously been observed in the PLT tokamak [8].

The longer wavelengths are shown in Figure 2. The Ti lines are here much weaker and, again, lines from other plasma impurities interfere with the titanium spectra. In this interval several strong lines from O V and O VI appear in second order. The Ti^{5+} line at 338.3 Å has not previously been observed and we use the NIST calculated wavelength for our identification.

Most of the 3p - 3d transitions listed in Table 1 are observed in SSPX spectra. The identification of a few lines are somewhat uncertain due to line blends. Due to blends and overlapping lines it is a difficult task to determine the intensity of the titanium lines and the charge state distribution. This is especially true for blends with oxygen lines, which always exist in the spectra. We are planning to further investigate the spectra from higher charge states of titanium present in SSPX as well as to perform collisional radiative modeling of the spheromak plasmas. This will help us better understand the M-shell emission from transition elements in high-density magnetic fusion plasmas.

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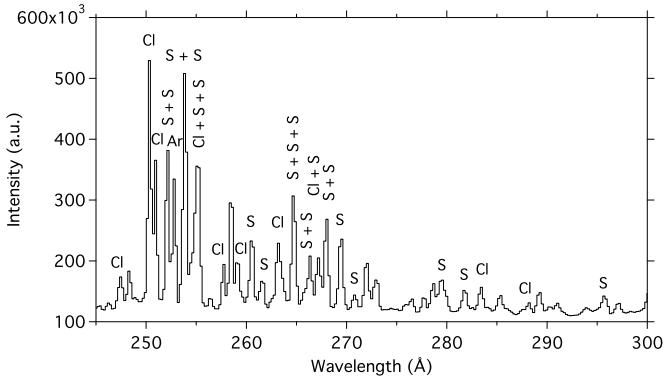

Figure 1. Spectrum from SSPX shot # 18633 showing strong titanium lines labeled according to charge state. Also shown are O V at 248.5 Å, and O IV at 272.1 and 279.8 Å.

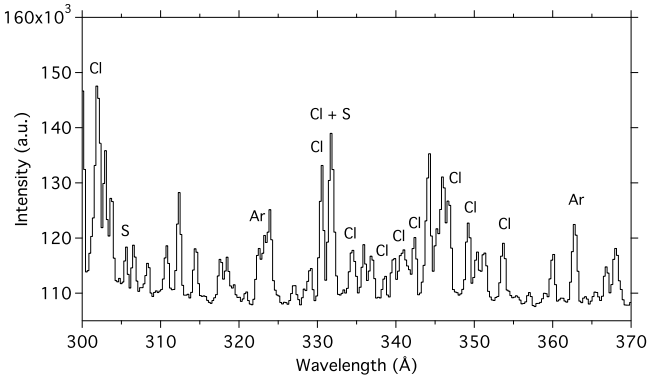

Figure 2. Spectrum from SSPX shot # 18633 showing strong titanium lines labeled according to charge state. Also shown are He II at 303.8 Å, C IV at 312.4 Å, and second order lines of O VI at 300.2, 346.0, 368.0 Å and O V at 303.0, 340.4, and 344.4 Å.

Ion	Lower level	Upper level	λ (Å)	Ion	Lower level	Upper level	λ (Å)
Ti^{4+}	$3s^23p^6\ {}^1S_0$	$3s^23p^53d\ {}^1P_1$	253.0	Ti^{6+}	$3s^23p^4\ {}^3P_1$	$3s^23p^3(^2P)3d\ {}^1D_2$	248.0
	${}^1S_0$	${}^3D_1$	323.4		${}^3P_2$	${}^3D_1$	250.9
	${}^1S_0$	${}^3P_1$	363.1		${}^3P_2$	${}^3D_2$	252.2
					${}^1D_2$	${}^1F_3$	252.3
Ti^{5+}	$3s^23p^5\ {}^2P_{3/2}$	$3s^23p^4(^1D)3d\ {}^2D_{3/2}$	247.5		${}^1S_0$	${}^1P_1$	252.6
	${}^2P_{3/2}$	${}^2D_{5/2}$	250.5		${}^3P_1$	${}^3D_1$	253.8
	${}^2P_{1/2}$	${}^2D_{3/2}$	251.1		${}^3P_2$	${}^3D_3$	254.0
	${}^2P_{3/2}$	${}^2P_{3/2}$	255.4		${}^3P_0$	${}^3D_1$	254.7
	${}^2P_{1/2}$	${}^2P_{1/2}$	257.9		${}^3P_1$	${}^3D_2$	255.1
	${}^2P_{1/2}$	${}^2P_{3/2}$	259.2		${}^1D_2$	${}^1D_2$	260.7
	${}^2P_{3/2}$	${}^2S_{1/2}$	263.2		${}^3P_2$	$3s^23p^3(^2D)3d\ {}^1P_1$	261.9
	${}^2P_{1/2}$	${}^2S_{1/2}$	267.3		${}^3P_2$	$3s^23p^3(^2P)3d\ {}^3P_1$	263.9
	${}^2P_{3/2}$	$3s^23p^4(^1S)3d\ {}^2D_{5/2}$	282.2		${}^3P_2$	${}^3P_2$	264.8
	${}^2P_{3/2}$	${}^2D_{3/2}$	283.6		${}^3P_1$	$3s^23p^3(^2D)3d\ {}^1P_1$	265.0
	${}^2P_{1/2}$	${}^2D_{3/2}$	288.4		${}^3P_1$	$3s^23p^3(^2P)3d\ {}^3P_0$	265.1
	${}^2P_{3/2}$	$3s^23p^4(^1D)3d\ {}^2F_{5/2}$	301.9		${}^3P_0$	$3s^23p^3(^2D)3d\ {}^1P_1$	266.0
	${}^2P_{3/2}$	$3s^23p^4(^3P)3d\ {}^2D_{5/2}$	330.7		${}^3P_2$	${}^3S_1$	266.5
	${}^2P_{3/2}$	${}^4P_{1/2}$	331.8		${}^3P_1$	$3s^23p^3(^2P)3d\ {}^3P_1$	267.1
	${}^2P_{3/2}$	${}^2D_{3/2}$	334.5		${}^3P_1$	${}^3P_2$	268.0
	${}^2P_{1/2}$	${}^4P_{1/2}$	338.3		${}^3P_0$	${}^3P_1$	268.1
	${}^2P_{1/2}$	${}^2D_{3/2}$	341.1		${}^1D_2$	${}^3D_2$	268.5
	${}^2P_{3/2}$	${}^2P_{3/2}$	342.6		${}^3P_1$	$3s^23p^3(^2D)3d\ {}^3S_1$	269.8
	${}^2P_{3/2}$	${}^2P_{1/2}$	346.7		${}^3P_0$	${}^3S_1$	270.7
	${}^2P_{1/2}$	${}^2P_{3/2}$	349.6		${}^1D_2$	${}^1P_1$	279.5
	${}^2P_{1/2}$	${}^2P_{1/2}$	353.9		${}^1D_2$	$3s^23p^3(^2P)3d\ {}^3P_1$	281.9
					${}^1D_2$	${}^3P_2$	282.9
					${}^1D_2$	$3s^23p^3(^2D)3d\ {}^1F_3$	296.1
					${}^1S_0$	${}^1P_1$	305.7
					${}^1D_2$	${}^1D_2$	332.1

Table 1. $3s^23p^{k-1}3d$ resonance transition arrays in Ti^{4+} through Ti^{6+}. Data from NIST.